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Palonen, Pauliina

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The influence of high tunnel on yield and berry quality in three floricane raspberry cultivars

Pauliina Palonen*, Anni Pinomaa, Tero Tommila

Department of Agricultural Sciences, PO Box 27, FI-00014 University of Helsinki, Finland

* Corresponding author, Tel.: +358 2941 58333, E-mail address: pauliina.palonen@helsinki.fi (P. Palonen)

Abstract

Growing raspberries in polyethylene tunnels is becoming more and more common. We wanted to examine the effect of high tunnel growing conditions on yield and berry quality in three floricane raspberry cultivars, ‘Glen Ample’, ‘Glen Dee’, and ‘Maurin Makea’, under Northern high-latitude conditions. Compared to the open field, fruit yield per cane was doubled in the tunnel. Fruit bioactive properties, including phenolic compounds and antioxidant activity, were not affected by the tunnel growing conditions. Of the cultivars investigated, ’Glen Dee’ fruit had the lowest concentration of total phenolics. In the open field, the total phenolics content in ‘Glen Ample’ berries was 48% higher than ‘Glen Dee’. Berries grown in the open field had higher contents of soluble solids (°Brix) and higher titratable acidity than those grown in the tunnel. Additionally, ‘Glen Ample’ and ‘Maurin Makea’ berries were sweeter than ‘Glen Dee’ berries. In conclusion, raspberry production in polyethylene tunnels may provide major benefits through increased fruit yield. While fruit bioactive properties were not affected, sensory taste may be different, however, as berry sweetness and acidity were decreased in the high tunnel.

Keywords: acidity, antioxidant activity, phenolics, Rubus idaeus, soluble solids

1. Introduction

Raspberry (Rubus idaeus) production in the world has nearly doubled over the past 20 years (FAOSTAT, 2016). Growing public awareness of the putative health benefits of berries and greater interest in healthy diets has increased the demand of the fruit. Raspberries are commonly sold in the fresh market, and long shelf life is an important quality parameter. Because of the superior fruit quality and shelf life when produced in a protected environment, more and more raspberries are grown in polyethylene tunnels. In some countries, in fact, this is a requirement set by the supermarkets. Polyethylene tunnels have also been reported to increase yields and extend the season (Hanson et al., 2011; Fernandez and Perkins-Veazie, 2013; Xu et al., 2014).

Many environmental parameters in the tunnel are different from the open field, including light intensity and quality, temperature, humidity, wind, as well as pest and disease pressures. In high tunnels, long cane plants are commonly used and grown in substrate. Little information, however, is available on the influence of these altered growing conditions on internal berry quality including taste, and nutritional and health-related compounds, especially in Northern high-latitude conditions.

The perceived sweetness in raspberry fruit comes from sugars, 40-50% being fructose, 30-40% glucose, and 10-20% sucrose (Wang et al., 2009). Acidity is caused by the high concentration of organic acids, citric acid being the most important. Usually warm and dry weather increases sugar content and decreases acidity in raspberry fruit (Jennings, 1988; Malowicki et al., 2008). However, lower sugar content was observed in the primocane-type raspberry ‘Polka’ fruit when grown in high tunnels compared to an open field environment (Król-Dyrek and Siwek, 2015). This study indicates parameters other than the temperature difference between the tunnel and open field influenced this quality trait.

Rubus berries are a rich source of antioxidants and other bioactive compounds. The most important antioxidants in raspberry fruit are phenolic compounds and ascorbic acid (vitamin C) (Beekwilder et al., 2005). Among the ten raspberry genotypes studied by Mazur et al. (2014a), the main phenolic compounds were ellagitannins (57 %) and anthocyanins (42 %). The contents of total phenolics, flavonoids, and anthocyanins may be used to describe the antioxidant activity and thus potential health benefits of raspberry fruit (Wang and Lin, 2000; Liu et al., 2002; Anttonen and Karjalainen, 2005). Antioxidant activity is strongly correlated with the total phenolic concentration in raspberries (Deighton et al., 2000; Connor et al., 2005).

Temperature has contrasting effects on bioactive compounds in raspberry fruit (Remberg et al., 2010). Lower temperatures increase berry size through increased moisture content, therefore decreasing concentrations of bioactive compounds when expressed on a fresh weight basis (dilution effect). Vitamin C was an exception, which increased even on a fresh weight basis at low temperatures. However, since large berry size is an important quality parameter for commercial production, Remberg et al. (2010) recommended relatively low temperatures, 12 to 18°C, during the ripening of raspberry fruit.

Remberg et al. (2010) also suggested that fluctuations in temperature may enhance the accumulation of bioactive compounds in raspberry fruit, especially when compared to constant temperatures. Interestingly, long day conditions during fruit growth have also been shown to increase the concentrations of vitamin C, total phenolics, organic acids, and antioxidant capacity, while reducing the sugar content in raspberry fruit (Mazur at al., 2014b). In addition to photoperiod, light spectral composition may also affect berry quality; in our previous study, ellagic acid in raspberry fruit was increased under the film absorbing far red light, while the sugar:acid ratio was slightly reduced (Palonen et al., 2011).

The aim of our present study was to examine how high tunnel growing conditions affect the yield and berry quality, including sugar content, acidity, and the contents of total phenolics, as well as the antioxidant capacity, in three floricane raspberry cultivars under Northern conditions.

2. Material and Methods

2.1. Plant material and experimental design

The experiment was conducted at the University of Helsinki research field in Viikki (60°13' N; 25°1' E) during growing season 2015 using floricane raspberry cultivars ‘Glen Ample’, ‘Glen Dee’, and ‘Maurin Makea’. The experiment was set up as an identical RCBD in a polyethylene tunnel and an adjacent open field. In each environment (tunnel versus field), plants were grown in three rows (blocks). In the tunnel environment, each row had five plants each of the three different cultivars, while in the open field, each row had six plants each of the three different cultivars. This experiment was part of a larger variety trial which included six different raspberry genotypes.

'Glen Ample' and 'Glen Dee' are releases by the James Hutton Institute, Scotland. 'Maurin Makea' was discovered as an open-pollinated seedling in a raspberry breeding population at the Natural Resources Institute, Finland and released in 1996. It is known for its excellent winter hardiness and good fruit flavor.

2.2. Growing conditions

The experiment was established in 2014 in sandy soil on a gentle South-facing slope. In the open field, the raised raspberry beds were covered with black woven polypropylene fabric (MyPex®). White clover (Trifolium repens, cv. Grassland Huia) at the rate of 10 000 seeds/m^2 was sown between the rows. The polyethylene tunnel (8 m × 35 m, 4 m high) was oriented South-to-North and covered with clear polyethylene (Folitec UV M 42, Folitec, Westerburg, Germany). In the tunnel, the plants were grown in 10-L pots filled with peat (OPM 630 W, Kekkilä Oy, Vantaa, Finland). The tunnel floor was covered with white woven polypropylene fabric (MyPex®). The three rows were spaced 2.40 m apart in the tunnel and 2.60 m apart in the open field. Plant spacing within a row was 40 cm in the tunnel and 50 cm in the open field.

Tunnel plastic was removed for the winter on 30 October 2014 and replaced on 27 April 2015. The tunnel was ventilated mainly through the tunnel doors at either end. Tunnel plants were fertigated through drip irrigation three times a day with a 0.01% compound fertiliser, Taimi-Superex (NPK 19–4.4–20.2 plus microelements) (Kekkilä Oy, Vantaa, Finland), from 16 May through 5 June, and with a mixture of Taimi-Superex and Turve-Superex (NPK 12–4.7–27.1 plus microelements) (0.08%) from 6 June through 19 August. Plants in the open field were fertigated through trickle irrigation system using the same fertilisers six times during the growing season. One to two floricanes per plant were grown in the tunnel and one to three in the open field. New primocanes were allowed to grow freely during the experiment.

A bumblebee (Bombus terrestris) hive (Minipol, Koppert Biological Systems, Romulus, MI, USA) was placed in the tunnel to ensure pollination. No chemical control of pests or diseases was used in the experiment. In the tunnel, biological pest control included Amblyseius cucumeris to control thrips, Phytoseiulus persimilis to control spider mites, and BerryProtect tubes containing different species (Aphidius ervi, A. matricariae, A.colemani, Ephedrus cerasicola, Praon volucre, Aphelinus abdominalis) were used to control aphids (Biotus Oy, Forssa, Finland).

Temperature data in the open field are from the Finnish Meteorological Institute (Figure 1). Tunnel temperatures were measured in 30-minute intervals throughout the experiment. Light spectral composition in the open field and the tunnel was recorded on 15 September 2015 (Figure 2).

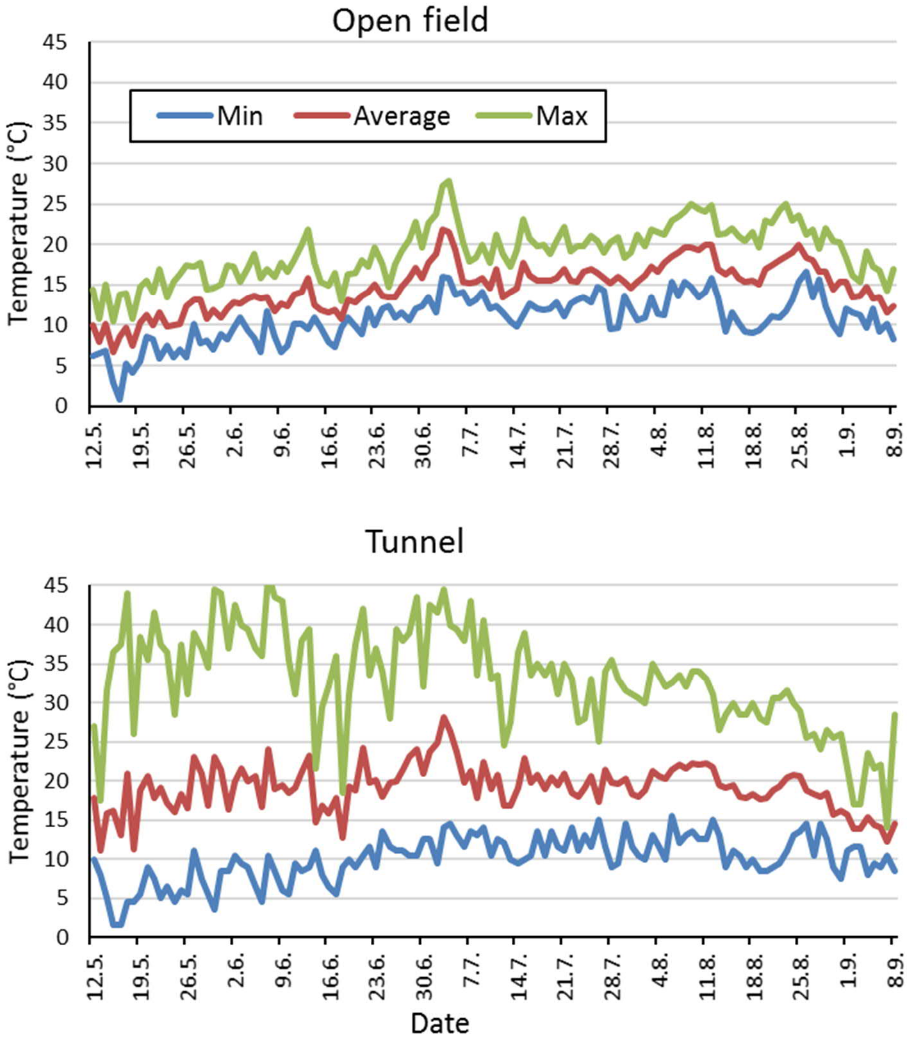

Figure 1. Daily average, minimum and maximum temperatures in the open field and high tunnel during the growing season 2015.

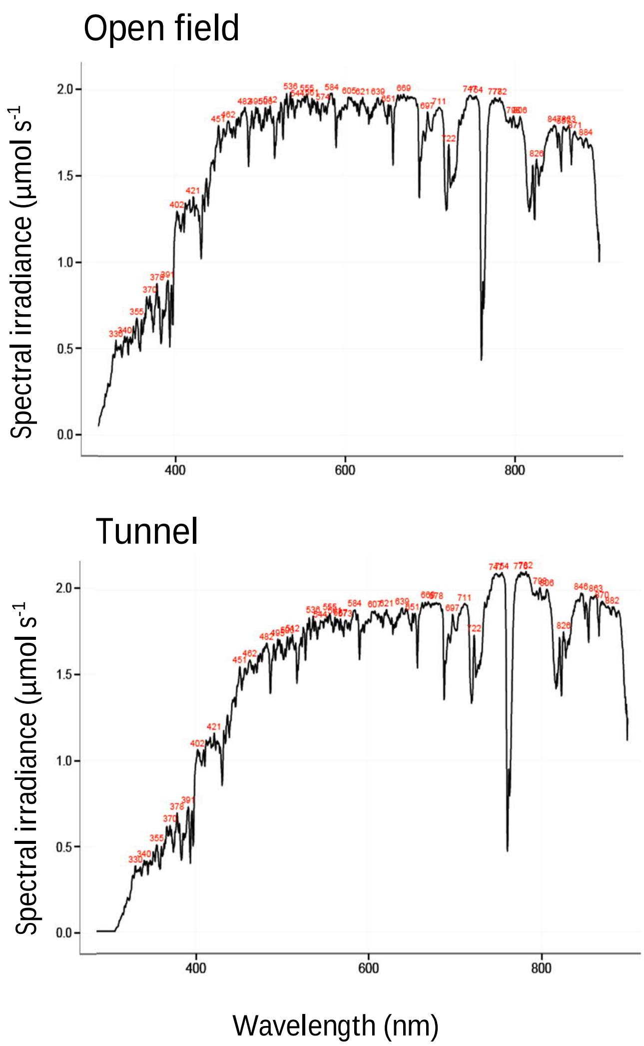

Figure 2. Spectral composition of light as a function of wavelength in the open field and high tunnel on 15 September 2015.

2.3. Harvesting and sample preparation

Raspberry fruits were harvested three times a week and were weighed and counted to determine total yield and the number of berries per cane. For chemical analyses of fruit quality, 150 to 200 g of berries per block were sampled and immediately frozen at -20 °C and held at -20 °C until analyses. To measure soluble solids (SS) and titratable acidity (TA), samples were taken four times during the harvest season, and three times for analyses of total phenolics and antioxidant capacity. Frozen berries were thawed at room temperature (22°C) four hours before sample preparation.

2.4. Chemical analyses of fruit quality

2.4.1 Soluble solids, pH and titratable acidity

Using a hand held potato presser, 100-120 g of fruit was macerated, and then incubated in a 100 ml decanter until the upper cloudy fraction could be discarded, the clear fraction of the sample being used for the analyses. Three replicate subsamples were taken and measured for their concentration of SS (°Brix) with an analogical refractometer (Master, Atago, Japan).

To measure TA, a 5.0 g aliquot of clear fruit juice was added to 25 ml of ultra pure water in a decanter. The pH was then measured with a Metrohm 744 pH meter (Metrohm AG, Herisau, Switzerland) and the TA was measured with a buret and 0.1 M NaOH. The amount of NaOH needed to reach a pH of 8.1 was quantified and used to calculate the concentration (w/w) of citric acid in the sample juice; in order to neutralise 1 mole of citric acid, three moles of NaOH is required.

2.4.2. Antioxidant activity and total phenolics

Using a blender (Waring Blendor Deluxe, Conair Corporation, NJ, USA), 100-120 g of fruit was pureed. The homogenised fruit puree (5 g) was extracted with 70% ethanol (15 ml) in a 50 ml tube at +4°C for 17 hours. According to Addai et al. (2013), recovery of antioxidant compounds using an ethanol extraction is sufficient for ferric reducing ability of plasma (FRAP) and total phenolics measurement. The samples were then centrifuged at 4600 rpm for 10 min and the pellet discarded. Lighting in the laboratory was kept dim and the tubes were wrapped in aluminum foil to prevent phenolic compounds from breaking down during the analysis. Extracts were stored at -20°C and always handled in low lighting.

Samples were diluted with ultra pure water 1:10 (v/v) to determine the FRAP using a modified version of the Benzie and Strain (1996) method. The FRAP reagent was prepared each day according to Benzie and

Strain (1996) and Deighton et al. (2000) protocols. We pipetted 1 ml of the FRAP reagent and 30 µl of sample into a cuvette and, after incubation for 4 min at room temperature, the absorbance at 593 nm was read using a spectrophotometer (UV 1601, Shimadzu, Japan). The antioxidant activity in the sample (FRAP) was expressed as µmol Fe(II)-TPTZ / g FW.

The concentration of total phenolics (TP) was determined using the Fast Blue BB (FBBB) method (Medina, 2011a). Since the optimal concentration of phenolics in the sample corresponds to a gallic acid concentration of 50-400 µg/ml (Medina, 2011b), samples were diluted with ultra pure water 1:10 (v/v). Next, 100 µl of 0.1% FBBB reagent and 100 µl of 5% NaOH were added into 1 ml of sample and the mixture was incubated at room temperature for 90 mins. The absorbance at 420 nm was then read using a spectrophotometer (UV 1601, Shimadzu, Japan). The concentration of TP in the sample was expressed as mg GAE/g FW.

2.5. Statistical analysis

The experimental design was a RCBD where the three blocks were nested in a growing condition treatment. The parameters of yield and berry quality were statistically analysed by a two-way ANOVA by means of a mixed model with growing condition treatment and cultivar as the fixed factors and block (nested in growing condition) as the random factor. The SAS Mixed procedure (SAS 9.4, SAS Institute Inc.) (Littell et al., 2006) was applied to fit the model using the restricted maximum likelihood (REML) estimation method. The data from the open field and the tunnel were analysed separately using ANOVA (IBM SPSS Statistics, program 23) with cultivar as an independent factor. In cases where conditions for analysis of variance were not fulfilled, a non-parametric Kruskal-Wallis test was used. Data for berry quality measurements from different dates were pooled and the means were used in the analyses. Cultivar means were separated using Tukey's test at a significance level of $P \leq 0.05$.

3. Results

3.1. Yield and berry size

Berries were harvested for 47 days in the open field and 62 days in the high tunnel. The harvest started with the cultivars ‘Glen Ample’ and ‘Maurin Makea’ on 1 July in the tunnel and 24 July in the open field (Fig. 3). For ‘Glen Dee’, the first berries were harvested on 13 July in the tunnel and 29 July in the open field. Total yield per cane across all cultivars was, on average, 99% higher in the tunnel compared to the open field ($P < 0.001$). This was due to the higher number of berries in the tunnel-grown canes ($P < 0.001$), since berry size was not affected by growing condition, but was significantly affected by cultivar ($P = 0.007$), with ‘Glen Dee’ having the largest berries. Cultivars differed in total yield ($P = 0.009$), as well as in their response to growing conditions due to a highly significant interaction observed between growing condition and cultivar ($P < 0.001$). Pronounced cultivar differences in the total yield were observed in the open field but not in the tunnel (Table 1). ‘Maurin Makea’ and ‘Glen Dee’ produced significantly lower yields in the open field than in the tunnel ($P < 0.001$), however, ‘Glen Ample’ was equally productive in both growing conditions (Fig. 3). For ‘Maurin Makea’, both berry number ($P = 0.001$) and berry size ($P < 0.001$) were smaller in the open field than in the tunnel. There was large variation in ‘Maurin Makea’ yield between the open field blocks, and a few berries suffered pest damage. Overall, berry weight declined as the harvest season progressed (Fig. 4). In the tunnel, some of the ‘Glen Ample’ fruit were crumbly, and, due to high variation, the differences in berry size between the cultivars were not significant in the tunnel.

Table 1. Total yield, number of berries and average berry weight in three raspberry cultivars grown in open field and high tunnel environments, 2015. The values are means of three replicates of five to six plants each and followed by ± SE.

	Yield (g/cane)	Number of berries /cane	Berry weight (g)
Open field			
'Glen Ample'	1003 ± 86 a	171 ± 4 a	5.6 ± 0.4 a
'Glen Dee'	367 ± 15 b	59 ± 1 b	6.2 ± 0.3 a
'Maurin Makea'	272 ± 20 b	71 ± 5 ab	3.6 ± 0.1 b
P	< 0.001	< 0.001	0.001
Tunnel			
'Glen Ample'	905 ± 102 b	224 ± 41	4.6 ± 0.8
'Glen Dee'	1272 ± 68 a	203 ± 5	6.3 ± 0.2
'Maurin Makea'	1082 ± 72 ab	227 ± 17	4.6 ± 0.1
P	0.052	Ns.	Ns.

Ns. = not significant

Cultivar means followed by a different letter, for both growing conditions separately, are significantly different at $P < 0.05$ by Tukey's test.

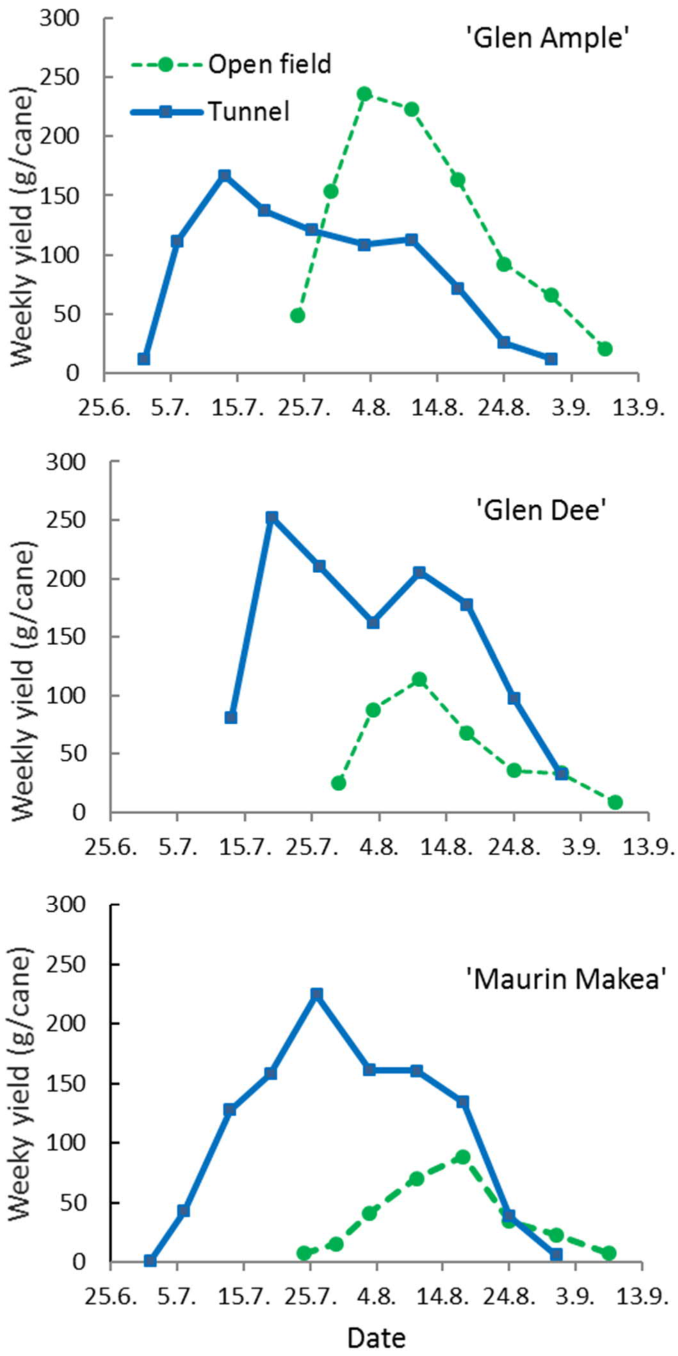

Figure 3. Weekly marketable fruit yield per cane in three raspberry cultivars grown in open field and high tunnel environments, 2015. The values are means of three replicates of five to six plants each.

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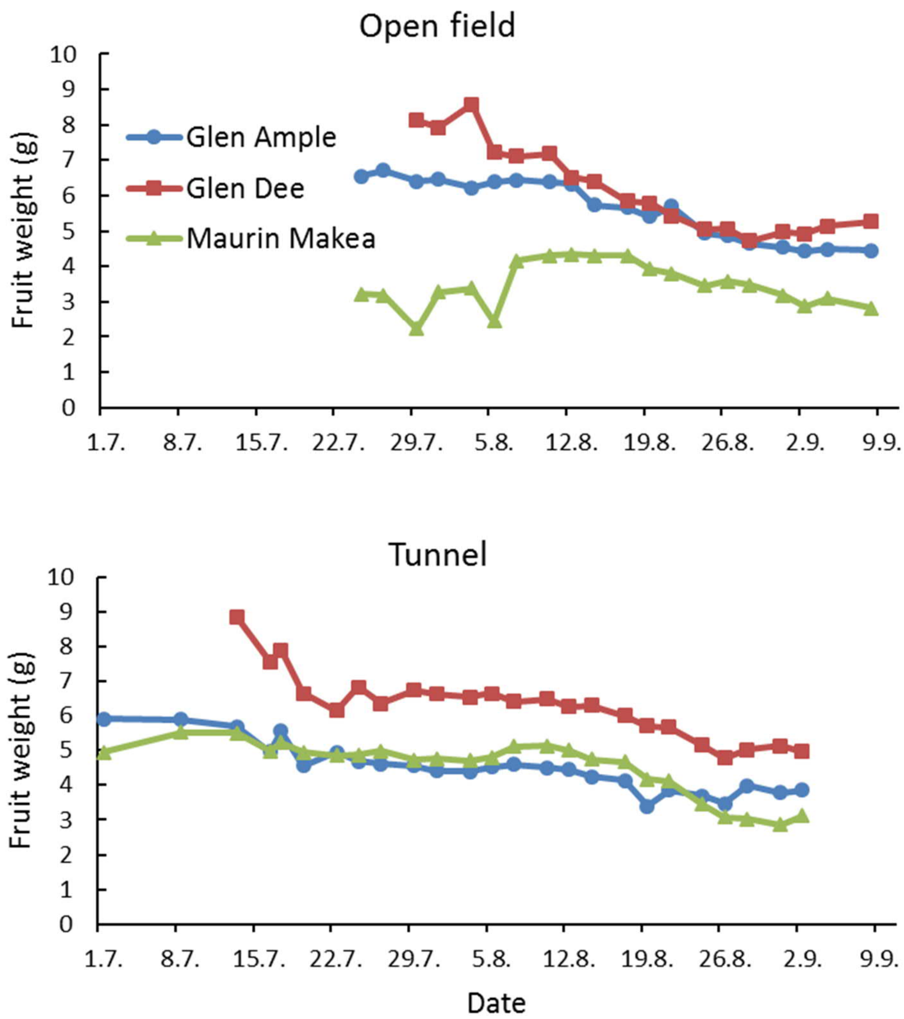

213 Figure 4. Average berry weight during the harvest season in three raspberry cultivars grown in open field
214 and high tunnel environments, 2015. The values are means of three replicates of five to six plants each.

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216 3.2. Berry quality

217 Berry sugar content and acidity were significantly affected by the growing conditions (Table 2). A higher
218 content of SS (°Brix) and TA were observed in berries from the open field, while the pH was lower. There
219 was no difference, however, in the sugar:acid ratio between the two growing conditions. Between the
220 cultivars, there were also differences; sugar content was lowest in 'Glen Dee' and the pH was lowest in
221 'Glen Ample' (Table 2).

In the open field, both pH (P = 0.002) and TA (P = 0.012) were significantly different between the cultivars, with a pH of 3.00 for 'Glen Ample', 3.05 for 'Maurin Makea' and 3.07 for 'Glen Dee'. 'Glen Dee' berries were also the least acidic based on the measurement of TA (Fig. 5). In the open field, the sugar content was highest for 'Maurin Makea' and lowest for 'Glen Dee', but, according to the Kruskal-Wallis test, the difference was not significant (P = 0.051). In the tunnel, the differences between the cultivars in sugar content, TA and pH were less pronounced and not significantly different.

Table 2. The influence of growing conditions (open field or high tunnel) and cultivar on the concentration of soluble solids (°Brix) and titratable acids (TA), sugar:acid ratio, and pH in raspberry fruit juice. The values are means of three replicates of five to six plants each and four sampling times, followed by ± SE.

	°Brix	TA (g/100 g FW)	Sugar:acid ratio	pH
Growing condition (G)				
Open field	10.0 ± 0.3	2.06 ± 0.03	4.86 ± 0.11	3.04 ± 0.01
Tunnel	8.6 ± 0.2	1.77 ± 0.02	4.88 ± 0.12	3.26 ± 0.01
P	< 0.001	< 0.001	Ns.	< 0.001
Cultivar (C)				
'Glen Ample'	9.5 ± 0.2 a	1.94 ± 0.07	4.93 ± 0.15	3.12 ± 0.05 a
'Glen Dee'	8.7 ± 0.3 b	1.87 ± 0.04	4.66 ± 0.09	3.17 ± 0.04 b
'Maurin Makea'	9.7 ± 0.6 a	1.94 ± 0.09	5.02 ± 0.14	3.17 ± 0.05 b
P	0.008	Ns.	Ns.	0.001
Interaction				
G × C	Ns.	0.006	Ns.	Ns.

Ns. = not significant

Cultivar means followed by a different letter are significantly different at P < 0.05 by Tukey's test.

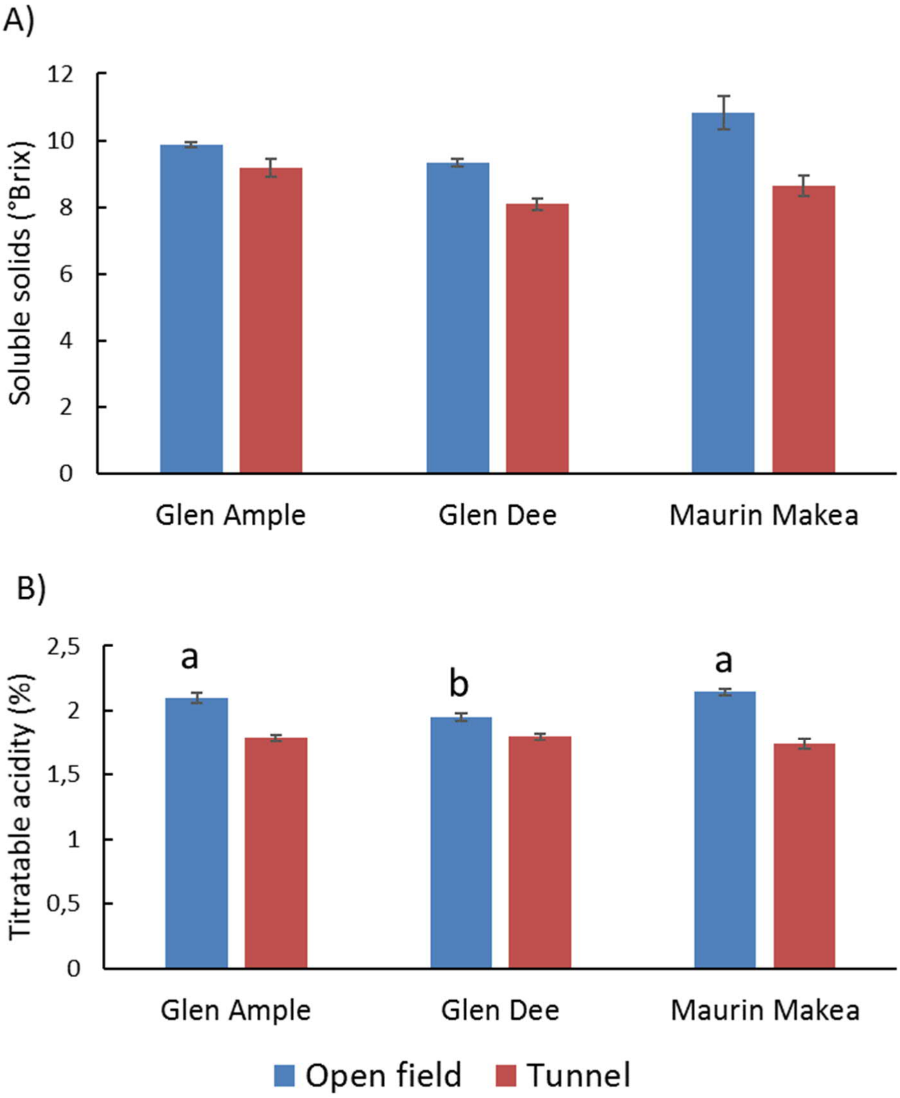

Figure 5. Concentrations of A) soluble solids (°Brix) and B) titratable acids (%) in the fruit juice of three raspberry cultivars grown in open field and high tunnel environments, 2015. The values are means of three replicates of five to six plants each and four sampling times. Vertical bars present ± SE. Cultivar means marked by a different letter, for both growing conditions separately, are significantly different at $P < 0.05$ by Tukey's test.

Examined all together, antioxidant activity was not affected by growing conditions or cultivar (Table 3). When analysing data from the two growing conditions separately, however, cultivar differences were observed in the open field ($P = 0.042$), with antioxidant activity being higher for ‘Glen Ample’ berries than ‘Glen Dee’ (Fig. 6).

The TP content was not affected by growing conditions, but was affected by cultivar, with ‘Glen Ample’ being significantly higher than ‘Glen Dee’ (Table 3). Furthermore, when the data from the two growing conditions were analysed separately, this cultivar effect was still found to be significant in the open field ($P = 0.018$), where ‘Glen Dee’ berries had the lowest concentration of TP (Fig. 6). Additionally, a correlation between antioxidant activity and the concentration of TP was also observed ($r = 0.59$, $P < 0.001$).

Table 3. The influence of growing conditions (open field or high tunnel) and cultivar on the antioxidant activity (FRAP) and concentration of total phenolics in raspberry fruit in 2015. The values are means of three replicates of five to six plants each and three sampling times and followed by ± SE.

	FRAP (µmol Fe(II)/g FW)	Total phenolics (mg GAE/g FW)
Growing condition (G)		
Open field	23.6 ± 0.5	3.8 ± 0.3
Tunnel	22.6 ± 0.7	4.1 ± 0.2
P	Ns.	Ns.
Cultivar (C)		
‘Glen Ample’	24.3 ± 1.1	4.4 ± 0.3 a
‘Glen Dee’	22.3 ± 0.3	3.3 ± 0.2 b
‘Maurin Makea’	22.7 ± 0.6	4.1 ± 0.2 ab
P	Ns.	0.011
Interaction		
G × C	Ns.	Ns.

Ns. = not significant

Cultivar means followed by a different letter are significantly different at $P < 0.05$ by Tukey’s test.

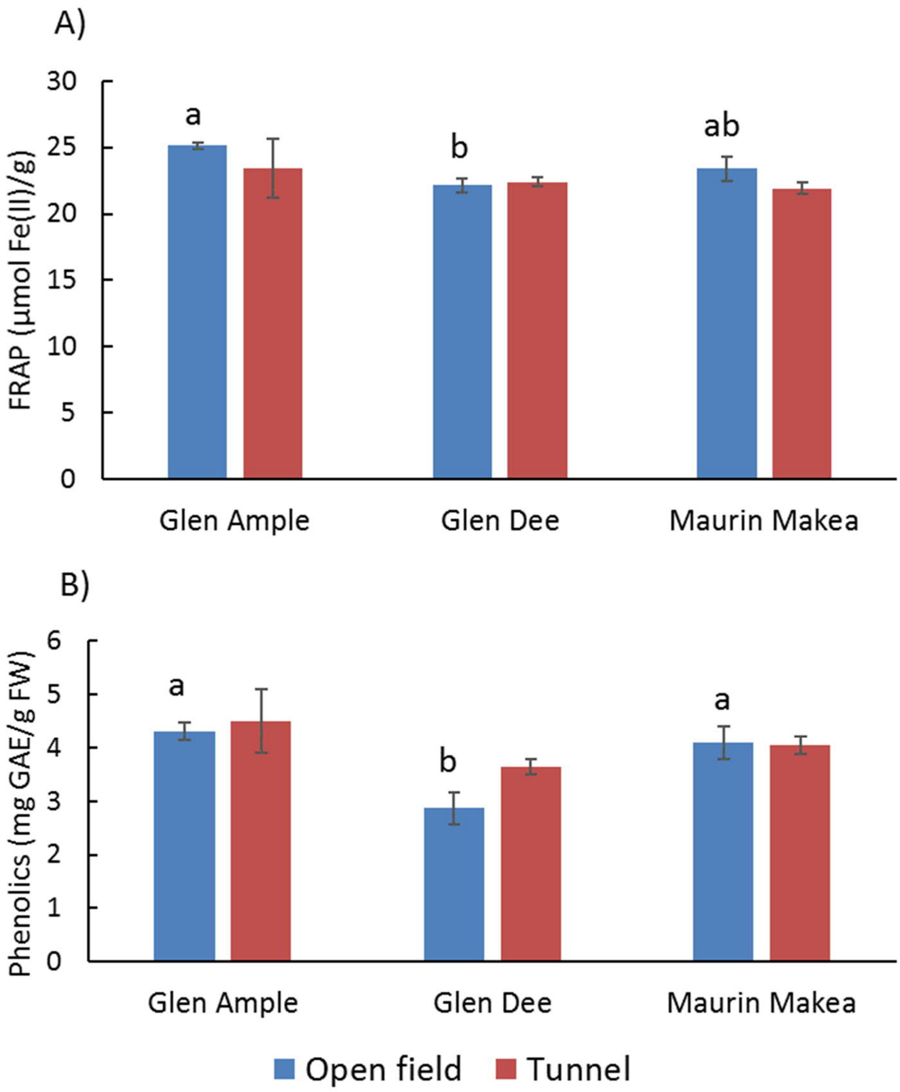

Figure 6. The A) antioxidant activity (FRAP) and B) concentration of total phenolics in the fruit of three raspberry cultivars grown in open field and high tunnel environments, 2015. The values are means of three replicates of four plants each and three sampling times. Vertical bars present ± SE. Cultivar means marked by a different letter, for both growing conditions separately, are significantly different at $P < 0.05$ by Tukey's test.

4. Discussion

To our knowledge, this is the first study to report the effect of protected cultivation of raspberry in polyethylene tunnels on fruit quality in Northern (60°13'N) conditions, where light conditions, including photoperiod and light spectral composition, are notably very different from other raspberry production areas. Fruit yield per cane was doubled in the tunnel compared to the open field. This has also been noted by previous studies for tunnel-grown floricane raspberry cultivars, with more than double higher yields seen by Hanson et al. (2011) in Michigan, USA, Fernandez and Perkins-Veazie (2013) in North Carolina, USA, and Xu et al. (2014) in Quebec, Canada. Cropping potential is largely determined by the conditions during the season preceding the harvest year. In our experiment, the plants were also grown in the same conditions the previous year. In an earlier study we observed that the number of flowers (cropping potential) in 'Maurin Makea' long cane plants increased by 28-40% in tunnel-grown canes compared to the field-grown canes, depending on the duration of cold storage (Palonen et al., 2015).

The temperatures inside the tunnel were relatively high, especially between late May and early July. Remberg et al. (2010) recommended relatively low temperatures, 12 to 18°C, for protected raspberry production since berry weight decreases with increasing post-flowering temperature. Although the temperatures recorded in our tunnel were much higher, the berry size was not reduced. In the study by Fernandez and Perkins-Veazie (2013), berry size was not affected by tunnel growing conditions either. Some of the 'Glen Ample' fruit in the tunnel were crumbly, a disorder that is increasingly common in Europe, and has recently been shown to depend on seasonal and environmental, as well as genetic, factors (Graham et al., 2015). The tunnel growing conditions may have influenced the expression of this condition in our experiment.

Berries grown in the open field had higher contents of SS (°Brix) and higher TA than those grown in the high tunnel, whereas the sugar:acid ratio was not affected. Furthermore, the differences between the cultivars regarding these attributes were more pronounced in the open field. Sugar content and acidity only partially explain sensory taste, with 15-20 volatile aroma compounds detected in raspberry fruit significantly affecting its flavor (Larsen and Poll, 1990). Sensory sweetness and sensory acidity do correlate with measured sucrose content and sugar:acid ratio (Stavang et al., 2015), although the sugar:acid ratio may be more closely related to fruit maturity.

Warm and dry weather increases sugar content and decreases acidity in raspberry fruit (Jennings, 1988). Malowicki et al. (2008) observed that, for raspberries grown in Oregon and Washington, the SS were higher and TA lower for the growing site with higher average temperatures. In our study, SS was, on average, 10.0% in the open field and 8.6% in the high tunnel, and was lowest for 'Glen Dee'. Lower SS in the tunnel compared to the open field has also been reported for the primocane-type raspberry 'Polka' in Poland (Król-Dyrek and Siwek, 2015). Norwegian researchers have reported SS contents of 8.3% for 'Glen Ample' in the open field (61°11'N) (Mazur et al., 2014a) and, in another study, 9.5% in a polyethylene tunnel (59°40'N) (Remberg et al., 2010). The SS for 'Glen Ample' in our study was 9.9% in the open field and 9.2% in the tunnel. The TA measured in our study for 'Glen Ample' in the open field was exactly the same (2.1 g/100 g FW) as observed in the open field in Norway (Mazur et al., 2014a). For cultivars 'Glen Clova' and 'Glen Prosen', TA concentrations of 1.3% and 2.0%, respectively, have been reported; the average for 40 red raspberry genotypes being 1.6% (Weber et al., 2008)

Raspberry plant photosynthesis declines as temperatures rise above 25°C (Stafne et al., 2001). It is possible that high temperatures inside the tunnel led to decreased transport of photosynthates into the fruit. Environmental conditions including temperature, light and humidity also affect the biosynthesis of flavor volatiles (Paterson et al., 2013). We observed that for some cultivars flavor did not develop as well in the tunnel as in the open field.

Fruit bioactive properties, including phenolic compounds and antioxidant activity, were not affected by the high tunnel. In 'Glen Ample' fruit, TP concentrations of 1.9 mg GAE/g FW in the open field (Mazur et al., 2014a) and 2.6 mg GAE/g FW in the tunnel (Remberg et al., 2010) have been reported. In these studies, the Folin-Ciocalteu method was used. In 'Glen Ample', we obtained measures of, on average, 4.4 mg GAE/g FW using the Fast Blue BB method which has been observed to yield a 2.6-fold increase in concentration of TP, compared to the Folin-Ciocalteu method (Lester et al., 2012). TP concentrations for 'Maurin Makea' and

'Glen Dee' fruit have not been previously reported in the literature, though, for 12 red raspberry cultivars grown in Eastern Finland, the phenolic concentrations ranged from 1.92 to 3.59 mg/g FW (Folin-Ciocalteu) (Anttonen and Karjalainen, 2005). Weber et al. (2008) reported TP concentrations of 3.78 and 3.70 mg / g FW in cultivars 'Glen Clova' and 'Glen Prosen', respectively; the average for 40 red raspberry genotypes being 4.21 mg / g FW. Comparing results from different studies is further complicated by the fact that the recovery of phenolic compounds, and thus their measured concentration, is dependent on the extracting solvent used (Addai et al., 2013).

Many environmental factors influence the biosynthesis of phenolic compounds in plants, and the regulation appears to be complex. High temperatures, for example, inhibit anthocyanin production in apple (Lin-Wang et al., 2011). On the other hand, in strawberry, high temperature (30/22°C day/night) increased the content of phenolic compounds and antioxidant capacity (Wang and Zheng, 2001). Additionally, an interaction between the genotype and environmental conditions on the antioxidant activity in raspberry was observed by Hanson et al. (2011). In our study as well, high temperatures inside the tunnel may have changed the fruit's chemical composition and relative amounts of individual phenolic compounds, although the total concentration of phenolics was not affected. Cultivar differences were pronounced, with 'Glen Ample' fruit having the highest concentration of TP and 'Glen Dee' the lowest. A direct relationship between the antioxidant capacity and the content of TP, especially anthocyanins and ellagitannins, has been shown for raspberry fruit (Wang and Lin, 2000; Liu et al., 2002; Remberg et al., 2010). A correlation was observed in our study as well. Antioxidant activity showed a trend similar to TP, although the differences between the cultivars were not as pronounced. Weber et al. (2008) reported FRAP values of 21 and 20 Trolox equivalents in cultivars 'Glen Clova' and 'Glen Prosen', respectively; the average for 40 red raspberry genotypes being 25. The average in our study was 23.1 µmol Fe(II)/g, across all cultivars and both growing conditions.

The data presented here can not be used to determine a single environmental factor that caused the differences in berry quality, but rather to compare two different production systems and environments.

Not only were temperature and light conditions, humidity and windiness different, but the plants were managed differently in each growing condition. Key production practices, such as irrigation, fertilization, and growth substrate were different. Furthermore, harvest maturity affects all these measured parameters. For example, TA decreases and the concentration of anthocyanins and the sugar:acid ratio (mainly due to decreasing acidity) increase during raspberry fruit maturation (Stavang et al., 2015). Therefore, it is crucial for the reliability of any analysis that sampled berries are in the same maturity range.

While the content and composition of phenolic compounds are certainly affected by environmental conditions, it appears that these characteristics are more greatly affected by genotype. Anttonen and Karjalainen (2005) reported large variation in fruit TP concentration between the raspberry cultivars grown in Finland, ranging from 192 mg/100 g (FW) in ‘Gatineau’ to 359 mg/100 g (FW) in ‘Ville’. Differences were also observed in the contents of quercetin, ellagic acid, and anthocyanins. In our study, the open field TP concentration of ‘Glen Ample’ was 48% higher than that of ‘Glen Dee’. The highest contents of phenolics have actually been measured in wild raspberry (Määttä-Riihinen et al., 2004). Weber et al. (2008) reported a threefold difference in FRAP values across red raspberry genotypes. Apparently, it is more important to consider the genotype grown than the influence of growing conditions, as genotype effects are far more significant.

In conclusion, raspberry production under polyethylene tunnels may provide major benefits, as fruit yield per cane was doubled in the tunnel compared to the open field, while fruit bioactive properties, including phenolic compounds and antioxidant activity, were not affected. Berries grown in the open field, however, contained more sugars and acids than the ones grown in the tunnel. Cultivar differences were pronounced, with ‘Glen Ample’ and ‘Maurin Makea’ berries having higher phenolic concentrations and being sweeter than ‘Glen Dee’ berries.

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